UNITED STATES DISTRICT COURT
EASTERN DISTRICT OF MICHIGAN
SOUTHERN DIVISION

3D Systems, Incorporated,	§	**Case No. 2:05-cv-74891**
Plaintiff,	§	**Hon. Avern Cohn**
v.	§	**Magistrate Judge Hon. R. Steven Whalen**
Envisiontec, Incorporated, ***et al.***	§	
Defendants.	§	

SPECIAL MASTER'S SUPPLEMENTAL REPORT INCLUDING CORRELATED CLAIM CHARTS AND IDENTIFICATION OF THE STRUCTURE DISCLOSED IN THE SPECIFICATION SUPPORT FOR THE MEANS-PLUS-FUNCTION LIMITATIONS OF THE '539 AND '143 PATENTS

Claim 35 of the'143 Patent

U.S. Patent No. 4,999,143	3D's Claim Construction	Defendant's Claim Construction	Special Master's Recommendation	Court's Interpretation
1 35. [An apparatus for **producing a three-dimensional object** from a medium capable of selective physical transformation	producing a product, prototype, or model which has three dimensions	moving a beam of radiation across the surface of a curable liquid to create a solid object by drawing a radiation pattern thereon	The phrase "producing a three-dimensional object" is unambiguous and need not be interpreted or limited.	
2 upon **exposure to synergistic stimulation**	subjected to (1) electro-magnetic radiation such as infrared radiation, visible radiation (*i.e.*, light), ultraviolet radiation or x-ray radiation; or (2) particle beams; or (3) reactive chemicals, to cause the building material to transform into a solidified state	having a radiation pattern drawn thereon with a radiation beam that moves across the surface of a curable liquid	The term "synergistic stimulation" embraces a moving beam of different wavelengths of electromagnetic radiation, a stationary source of different wavelengths of electromagnetic radiation, electron beams, a cathode ray tube, ink jets, and reactive chemicals.	
3 from an object representation specifying a first object surface to be spaced from a second surface by a spacing, and at least partially opposing the second surface, comprising:	from data representing the three dimensional object	from data files representing horizontally-sliced object sections of constant thickness	The phrase "from an object representation" means data that represents adjacent or successive cross sections of the object. The compilation of the object data into slices or layers is crucial to the disclosed stereolithographic process. This meaning also comports with the later description in Limitation 8 of this claim of the receiving and forming means as comprising "means for forming said object substantially layer by layer."	

4 at least one **computer programmed to form a support representation**	computer having instructions to produce data relating to a support	a computer programmed to provide data files representing horizontally-sliced sections of constant thickness of a structure that has a long, slender, rectangular cross-section and which provides reinforcement to the object or portions of the object	This claimed element is expressed clearly. It means a computer programmed or having instructions to produce data relating to a support for the three-dimensional object.	
5 specifying a **removable support**	structure that is not part of the finished object which provides reinforcement to the object or portions of the object and is capable of being separated from the object	a structure that has a long, slender rectangular cross-section, which is not part of the finished object, which provides reinforcement to the object or portions of the object, and which is easily separated from the object.	3D has provided the correct interpretation of this limitation.	
6 to be **formed in said spacing out of a material substantially layer by layer,**	created in the space between the first and second surfaces by successive thickness of a building material	created in the space between the first and second surfaces by successively solidifying curable liquid sections of constant thickness	The support is created in the space between the first and second surfaces by successively solidifying curable liquid cross sections.	
7 said support in cross sectional width being **thin**, and comprising a solid which extends along a path connecting said first and second surfaces, the path having a vertical path component which is greater than any horizontal path component; and	substantially lesser in width than in length and easy to remove after the object is formed	not greater than 1-mil CAD (computer aided design) thickness	In the context of the '143 Patent and its file history, the word "thin" means substantially smaller in width than in length to facilitate the easy removal of the support from the object.	
8 means for receiving said support representation, and for forming said three-dimensional object out of said medium <u>substantially layer by layer</u>, and also for forming said support out of said material substantially layer by layer, in accordance with said	§ 112 ¶ 6 means-plus-function: <u>function</u>: receiving the support representation, forming the three-dimensional object out of the medium, and also forming	§ 112 ¶ 6 means-plus-function: <u>function</u>: <u>structure</u>: includes the following elements: (1) computer programmed to	This clause is a means-plus-function clause. The identified functions are as follows: receiving the support representation; and forming the three-dimensional object and the support out of the	

object and support representations;	the support out of the material substantially layer by layer, in accordance with the object and support representations structure: computer control system as well as the source of synergistic stimulation and the platform that moves the object **3D: This structure is described in the '143 Patent at col. 8 ll. 56-59, col. 11 l. 46 - col. 12. 1.2, col. 13 11. 17-21, and shown in the drawings at Figs. 1, 4 and 5, attached at Exhibit C1 to the parties' submission**	receive the data files representing the horizontally-sliced support sections of constant thickness and convert them to vectors, (2) a radiation beam that is configured to move across the surface of a curable liquid to sequentially solidify support sections of constant thickness by drawing a radiation pattern dictated by the vectors, (3) a curable liquid, (4) a control system for moving the beam of radiation, and (5) a control system for moving the platform vertically **Envisiontec: This structure is described in the '143 Patent at _________, attached at Exhibit C2 to the parties' submission**	material substantially layer by layer in accordance with the object and support representations. The means includes a computer programmed to receive data files representing (a) cross sections of the object and (b) cross sections of the support, a fluid medium capable of solidification in response to synergistic stimulation, and a source of synergistic stimulation to which the material is exposed to form successive solidified layers, each at the surface of the last formed building material layer and each representing an adjacent cross section of the object and support, respectively. **This structure is shown in Figures 3-6 of the drawings and described in the corresponding text at col. 10, ll. 14-56, col. 11, l. 46 to col. 14, l. 56 attached as Exhibit C3 to this claim chart.**	

Claim 81 of the '537 Patent

U.S. Patent No. 5,902,537	3D's Claim Construction	Defendants' Claim Construction	Special Master's Recommendation	Court's Interpretation
1 81. An apparatus for **forming at least a portion of a three-dimensional object**	forming a part or all of a product, prototype, or model which has three dimensions	moving a beam of radiation across the surface of a curable liquid to create part of all of a solid object by drawing a radiation pattern thereon	The preamble (Limitations 1, 2 and 3) fairly describes stereolithography as that term has been defined and used consistently throughout the four patents that 3D has designated for trial. To the extent that the preamble might be clarified for ease of understanding it can be rewritten this way: "An apparatus for making all or part of a three-dimensional object by solidifying successive cross sections of the object from a curable liquid upon exposure to synergistic stimulation."	
2 on a substantially **cross-sectional basis**	the object is built by adding successive cross-sections to one another [original] object sections which cut across an axis of the object being built	sequentially solidifying adjacent, horizontally sliced object sections of constant thickness	3D has provided the correct interpretation of this limitation. Envisiontec's interpretation incorrectly reads into this phrase the extraneous limitations "horizontally" and "constant."	
3 from a material capable of physical transformation upon **exposure to synergistic**	subjected to (1) electro-magnetic radiation such as infrared radiation, visible radiation (*i.e.*,	having a radiation pattern drawn thereon with a radiation beam	3D has provided the correct interpretation of this limitation.	

stimulation, comprising:	light) ultraviolet radiation or x-ray radiation; (2) particle beams; or (3) reactive chemicals, to cause the building material to transform into a solidified state	that moves across surface of a curable liquid		
4 means for supplying data descriptive of the object;	§ 112 ¶ 6 means-plus-function: <u>function</u>: supplying data descriptive of the object <u>structure</u>: CAD file for storing the design data representing the object, and equivalents thereof **3D: This structure is described in the '537 Patent at col. 1 ll. 29-33 and col. 2 ll. 15-18, attached at Exhibit A1 to the parties' submission.**	§ 112 ¶ 6 means-plus-function: a computer programmed to generate data files representing horizontally-sliced object sections of constant thickness **Envisiontec: This structure is described in the '537 Patent at ________, attached at Exhibit A2 to the parties' submission.**	The means referred to is a computer or equivalent that supplies data that is descriptive or representative "of adjacent cross sectional layers of the object." This interpretation is consistent with the invention of the '537 Patent and provides an antecedent basis for the function of the source of synergistic stimulation claimed in the last limitation (Nos. 11, 12 and 13) of this claim. **This structure is described in the '537 Patent at col. 1, ll. 29-36, attached as Exhibit A3 to this claim chart.**	
5 a container for containing a volume of material having a working surface;			No interpretation is necessary	
6 an applicator	a device which applies and smoothes the building material [agreed]	a device which applies and smoothes the building material [agreed]	The parties agree that the element is a device that applies and smoothes the building material.	
7 for forming layers of material	forming a thickness of unsolidified building material	depositing sections of constant thickness	No interpretation is required.	

8 **over at least portions of previously formed object cross sections,** the applicator having a bottom opening located in proximity to the working surface;	over at least parts of layers of building material that have been previously solidified	on top of part or all of previously solidified horizontally-sliced object sections of constant thickness	The function may be expressed as "coating a building material layer on top of part or all of a previously solidified object cross section."	
9 a **vacuum pump** coupled to the applicator for drawing up material from the working surface through the bottom opening and into the applicator	device which creates a difference in pressure	pump that exhausts gas from an enclosed space	The definition of "vacuum pump" is found in the '537 Patent. It means a device that creates a difference in pressure. It is because of the pressure difference that "building material will be drawn up into applicator 310." ('537 patent, col. 38, ll. 20-45)	
10 **means for sweeping the applicator across at least a portion of at least some of the previously formed object cross sections**; and	§ 112 ¶ 6 means-plus-function: function: sweeping the applicator across at least a portion of at least some of the previously formed object cross-sections structure: (1) a frame and drive system; and (2) a frame and motor-driven threaded drive staff; and equivalents thereof **3D: This structure is described in the '537 Patent at col. 37 ll. 65-67 and the incorporated 5,174,931 Patent at col. 8 ll. 17-26, attached at Exhibit B1 to the parties' submission.**	§ 112 ¶ 6 means-plus-function: a frame and motor-driven threaded shaft that sweeps the applicator across all or part of at least some of the previously solidified, horizontally sliced object sections **Envisiontec: This structure is described in the '537 Patent at ________, attached at Exhibit B2 to the parties' submission.**	The language of this means-plus-function element may be defined as a "frame and motor-driven threaded shaft system" and equivalents thereof that perform the sweeping function recited in the claim. **This structure is described in the incorporated U.S. Patent No. 5,174,931 at col. 8, ll. 17-26 and shown in Figure 2, attached as Exhibit B3 to this claim chart.**	
11 **a source of synergistic stimulation**	a device that generates the synergetic stimulation	a beam of radiation configured to move across the surface of a curable liquid and draw	This element means a device that generates synergistic stimulation. The device may be a	

		a radiation pattern thereon	stationary or moving light source, a particle beam generator or a source of reactive chemicals.	
12 **for exposing the layers according to the descriptive data, to form the at least portion of the object from**	subjecting the unsolidified thicknesses of the building material to the synergistic stimulation in accordance with the design data representing the object	moving a beam of radiation across the surface of a curable liquid to draw a radiation pattern on the unsolidified curable liquid sections of constant thickness according to the data files representing horizontally-sliced object sections of constant thickness	This function may be interpreted to read: "for exposing the layers of curable liquid according to the data descriptive of adjacent cross sectional layers of the object referred to in Limitation 4 of this claim to form the at least portion of the object."	
13 **a plurality of object cross sections**	sections cut across an axis of the object	several horizontally-sliced object sections of constant thickness	See Limitation 12.	

Claim 2 of the '934 Patent

U.S. Patent No. 5,651,934	3D's Claim Construction	Defendants' Claim Construction	Special Master's Recommendation	Court's Interpretation
1[1] 2. A method for **stereolithographically forming a portion of a three-dimensional object**	successively curing a plurality of layers of a curable medium to form a portion of a product, prototype, or model which has three dimensions	moving a beam of radiation across the surface of a curable liquid to create part of a solid object by drawing a radiation pattern thereon	3D's construction accurately describes the patented stereolithographic process. Envisiontec's construction incorrectly limits the patented process to one of the several sources of synergistic stimulation disclosed in the '934 Patent.	
2 wherein a **subsequent layer** of the three-dimensional object	a new thickness of building material	a new section of constant thickness	3D's construction accurately describes this phrase. Envisiontec's construction incorrectly reads the limitation "constant" into the claim.	
3 is **formed over** a	covers	solidified on top of	A subsequent layer of the three-dimensional object is formed over a previously formed layer. "Formed over" means "formed on top of."	

[1] Each claim limitation has been numbered for referencing purposes.

4 **previously formed layer** of the object, comprising the steps:	a previously cured thickness of building material	previously solidified object section of constant thickness	No interpretation is necessary. Envisiontec reads the limitation "constant" into the claim without justification.	
5 a) holding a volume of a building material having a working surface wherein the building material is capable of selective physical transformation upon **exposure to prescribed synergistic stimulation;**	being subjected to predetermined (1) electromagnetic radiation such as infrared radiation, visible radiation (*i.e.*, light), ultraviolet radiation or x-ray radiation; or (2) particle beams; or (3) reactive chemicals, to cause the building material to transform into a solidified state	having a pattern of radiation drawn at selected locations on the surface thereof with a beam of radiation that moves across the surface of the curable liquid.	The term "synergistic stimulation" embraces electromagnetic radiation emitted by stationary and moving visible and invisible light sources, particle beams, and reactive chemicals. The word "exposure" means "being subject to."	
6 b) **forming a uniform coating of desired layer thickness over the previously formed layer,**	applying a substantially consistent layer of uncured building material of a predetermined thickness over the previously cured thickness of building material	creating a level, liquid section of constant selected thickness on top of a previously solidified object section of constant thickness by overdipping the object platform by more than the selected constant thickness of the next object section and then raising the platform to a point that is below the surface of the liquid by a distance equal to the selected constant thickness	The term "uniform" means a smooth, level coating. After the word "coating," the phrase "of uncured building material" could be added for greater clarity of meaning. Envisiontec's interpretation incorrectly adds structural and process limitations into this limitation.	
7 including **sweeping a [smoothing element]** <u>**winged blade**</u> at least once	**sweeping a smoothing element:** moving an element across the uncured building material to sweep away excess material to smooth the surface of the uncured building material	**sweeping a smoothing element:** sweeping away excess curable liquid by moving a device having the structure of Figures 26 or 27 of the '934 patent, or structural equivalents thereof,	The step of sweeping means that a device having a winged blade with sides that are at angles with respect to the surface of the material is moved across the upper surface of uncured building material to sweep away excess curable liquid and	

		across the surface of the curable liquid to create a level surface	thereby create a uniform coating of desired or predetermined thickness over the previously cured layer of building material.	
8 over the previously formed layer,	over the previously cured thickness of building material	on top of the previously solidified object section of constant thickness	No interpretation is required except for the term "over," which means "on top of."	
9 said [smoothing element] <u>winged blade</u> having a plurality of substantially separate members on a lower surface thereof for contacting the building material; and	**said smoothing element having a plurality of substantially separate members:** the smoothing element has at least two members which are spaced from each other	**said smoothing element having a plurality of substantially separate members:** a device having the structure of Figures 26 or 27 of the '934 patent or equivalents thereof which contacts the curable liquid to sweep away excess material and create a level surface	See interpretation of Limitation 7.	
10 c) **applying a prescribed pattern of synergistic stimulation** to the building material at the working surface to transform at least a portion of the building material	subjecting the building material to a specified pattern of (1) electromagnetic radiation such as infrared radiation, visible radiation (*i.e.*, light), ultraviolet radiation or x-ray radiation; or (2) particle beams; or (3) reactive chemicals, to cause the building material to transform into a solidified state	moving a beam of radiation across selected locations on the surface of a curable liquid to draw a radiation pattern thereon	This step covers electromagnetic radiation emitted by stationary and moving sources of visible and invisible light, particle beams, and reactive chemicals. Envisiontec has erroneously limited this step to one of the several techniques disclosed in the patent that may be used to apply the synergistic stimulation, namely, a moving beam of radiation.	

11 to form the subsequent layer.	form the new thickness of building material	solidify the new object section of constant thickness	"To form the subsequent layer" means simply the solidification or curing of the uniform coating of desired layer thickness.	

Claim 11 of the '981 Patent

U.S. Patent No. 5,630,981	3D's Claim Construction	Defendants' Claim Construction	Special Master's Recommendation	Court's Interpretation
1 11. [A method of **producing a three-dimensional object** from a [medium] <u>photopolymer</u> capable of selective physical transformation[1]	Not a limitation, but if deemed a limitation, then: producing a product, prototype, or model to be made which has three dimensions	moving a beam of radiation across the surface of a curable liquid to create a solid object by drawing a radiation pattern thereon	The preamble of claim 11 requires no interpretation. As to the term photopolymer, a photopolymer is a light sensitive plastic that cures or solidifies when exposed to light.	
2 when **subjected to [prescribed radiation]** <u>**light**</u>, said method comprising the steps of:	**subjected to prescribed radiation:** exposed to predetermined (1) electromagnetic radiation such as infrared radiation, visible radiation (*i.e.*, light), ultraviolet radiation or x-ray radiation; or (2) particle beams, to cause the building material to transform into a solidified state	**subjected to prescribed radiation**: having a radiation pattern drawn at selected locations on the surface thereof with a beam of radiation that moves across the surface of the curable liquid	The term "light" embraces light that is visible or invisible to the human eye, *e.g.*, ultraviolet light. "Subjected to" has the same meaning as exposed.	
3 providing said [medium]: <u>photopolymer</u>			No interpretation is necessary.	
4 **providing said [prescribed radiation]** <u>**light**</u>;	**providing said prescribed radiation**: providing the predetermined (1) electro-magnetic radiation such as infrared radiation, visible radiation (*i.e.*, light), ultraviolet radiation or x-ray radiation; or (2) particle beams, to cause the building	**providing said prescribed radiation**: providing the beam of radiation which is configured to move across the surface of the curable liquid and draw a pattern of radiation at selected locations thereon	The source of the light may be stationary or moving.	

[1] Words in **bold** are the disputed claim terms. Words in [brackets] and <u>underlining</u> show where limitations from the dependent claims were incorporated into the claim by the Special Master.

	material to transform into a solidified state			
5 **providing data representing the three-dimensional object to be formed which was generated on CAD system;**	providing design data corresponding to the object	supplying an object representation comprising horizontally-sliced object sections of constant thickness	This limitation should be interpreted as though it included the qualifying phrase "adjacent cross sectional layers of" after the word "representing." This construction comports with the disclosed invention of the '981 patent. This construction also provides an antecedent basis for Limitation 12 of Claim 11 which sets forth the step of "forming and adhering successive cross sectional layers. . . . by exposing the photopolymer to said light in response to said data." In the circumstances, the data representing the three-dimensional object referred to in this step must be data that is representative of adjacent cross sectional layers of the object.	
6 **forming a first cross-sectional layer** of structure by	forming an initial thickness of solidified building material representing a cross-section of the object	forming a first horizontal object slice of constant thickness	As a matter of clarification, "forming" means curing or solidifying. A cross sectional layer is a section of the three-dimensional object made by a plane cutting through the object.	

7 **exposing said [medium]** <u>photopolymer</u> to said **[prescribed radiation]** **<u>light</u>**	exposing the building material to the "prescribed radiation"	moving a beam of radiation across the selected locations on the surface of the curable liquid to draw a radiation pattern thereon	The word "exposing" means "subjecting to."	
8 **forming successive layers of [medium]** <u>photopolymer</u> adjacent to any	**forming successive layers of medium**: forming additional thicknesses of the building material	**forming successive layers of medium**: forming additional, curable liquid sections of constant thickness	No interpretation is necessary with the clarification of the word "forming" provided above.	
9 **previously formed cross-sectional layers** of structure	thicknesses of the building material that have already been solidified	previously solidified, horizontally-sliced object sections of constant thickness	No interpretation is necessary with the clarification of the word "forming" provided above.	
10 **forming and adhering successive cross-sectional layers** of structure	forming and integrating additional thicknesses of solidified building material	forming and adhesively attaching additional horizontally-sliced object sections of constant thickness	No interpretation is necessary with the clarification of the word " forming" provided above. The word "adhering" is a commonly understood word that means to join, stick together or integrate.	
11 to any **previously formed cross-sectional layers** of structure	thicknesses of the building material that have already been solidified	previously solidified, horizontally-sliced object sections of constant thickness	No interpretation is necessary with the clarification of the word " forming" provided above.	

12 by **exposing said [medium]** <u>**photopolymer**</u> **to said [prescribed radiation]** <u>**light**</u> **in response to said data.**	**exposing said medium to said prescribed radiation in response to said data:** subjecting the building material to the predetermined (1) electromagnetic radiation such as infrared radiation, visible radiation (*i.e.*, light), ultraviolet radiation or x-ray radiation; or (2) particle beams, in accordance with the design data corresponding to the object	**exposing said medium to said prescribed radiation in response to said data:** moving the beam of radiation across the selected locations on the surface of the curable liquid to draw a radiation pattern thereon based on the horizontally-sliced object sections of constant thickness	The "said data" referred to in this last step of Claim 11 is the data of Limitation 5, namely, the data which is representative of adjacent cross sectional layers of the object.	
13 whereby a **plurality of adhered cross sectional layers** of structure form the three-dimensional object.	two ore more thicknesses of solidified building material that have been integrated	several adhesively attached, horizontally-sliced object sections of constant thickness.	"Adhered cross sectional layers" means that the layers are joined together, stuck together or integrated to create the three dimensional object.	

EXHIBIT A3

Special Master's Specification Support for the '537 Patent, Claim 81, Means-Plus-Function Limitation 4:

- **'537 Patent (cover page)**
- **'537 Patent, col. 1, ll. 29-36**

US005902537A

United States Patent [19]

Almquist et al.

[11] **Patent Number: 5,902,537**

[45] **Date of Patent: May 11, 1999**

[54] **RAPID RECOATING OF THREE-DIMENSIONAL OBJECTS FORMED ON A CROSS-SECTIONAL BASIS**

[75] Inventors: **Thomas A. Almquist**, San Gabriel; **Charles W. Hull**, Santa Clarita; **Jeffrey S. Thayer**, Simi Valley; **Richard N. Leyden**, Topanga Canyon; **Paul F. Jacobs**, La Crescenta; **Dennis R. Smalley**, Newhall, all of Calif.

[73] Assignee: **3D Systems, Inc.**, Valencia, Calif.

[21] Appl. No.: **08/790,005**

[22] Filed: **Jan. 28, 1997**

Related U.S. Application Data

[63] Continuation of application No. 08/382,268, Feb. 1, 1995, abandoned.

[51] **Int. Cl.**[6] **B29C 35/08**; B29C 41/02

[52] **U.S. Cl.** **264/401**; 264/40.1; 264/308; 364/468.27; 425/135; 425/174.4

[58] **Field of Search** 264/40.1, 308, 264/401; 425/135, 174.4; 364/468.27

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[57] **ABSTRACT**

Methods and apparatus for use in building three-dimensional objects on substantially a cross-sectional basis including methods and apparatus for forming successive layers using counter-rotating rollers, ink jet recoaters, spinning members which sling material, applicator bars that dispense material via a meniscus and/or independently dispensed streams, and also including methods and apparatus to determine a preferred region over which to form a layer and to check for building errors.

82 Claims, 23 Drawing Sheets

RAPID RECOATING OF THREE-DIMENSIONAL OBJECTS FORMED ON A CROSS-SECTIONAL BASIS

This application is a continuation of Ser. No. 08/382,268, filed Feb. 1, 1995, now abandoned.

1. FIELD OF THE INVENTION

The current invention relates generally to the field known as rapid prototyping and manufacturing ("RP&M"), stereolithography or solid imaging, which involves the fabrication of three-dimensional objects on substantially a cross-section by cross-section basis. More particularly, the current invention relates to improved methods and apparatus for providing a layer of building material adjacent to an already-formed object cross-section, in preparation for forming a successive object cross-section out of the layer of building material.

2. BACKGROUND OF THE INVENTION

Solid imaging generally involves the formation of three-dimensional objects according to computer commands based on a computer aided design ("CAD") or other three-dimensional representation of the object. One solid imaging technique recently developed is stereolithography which is described in U.S. Pat. Nos. 4,575,330 and 5,184,307, both of which are incorporated by reference as if fully set forth herein. Appearing below is a summary of the basic steps of a stereolithographic embodiment:

1. Generation of a three-dimensional object design in a CAD system and storage of the design data in a CAD file;
2. Compiling data from the CAD file into numerous thin "slices" each representing a thin cross-sectional layer of the three-dimensional object;
3. Transfer of the compiled CAD data to a StereoLithographic Apparatus ("SLA");
4. Coating a layer of building material adjacent to a previously formed object cross-section in preparation for forming a subsequent object cross-section. The building material layer is preferably uniformly coated at an appropriate thickness so that the subsequently formed object cross-section meets tolerance requirements;
5. Selectively exposing the building material layer to synergistic stimulation to solidify or otherwise physically transform the building material layer at those locations which collectively represent the object cross-section to be formed;
6. Repeating steps (4) and (5) to alternately form successive building material layers and object cross-sections until the three-dimensional object is formed; and
7. Post processing the newly-formed object by removing residual building material clinging to the object, removing the object from the platform on which it was formed, exposing the object to additional synergistic stimulation to ensure complete solidification of the building material and removing supports.

Building materials typically used in solid imaging may exhibit fluid-like characteristics but solidify or otherwise physically transform in response to synergistic stimulation. The fluid-like characteristics facilitate dispensing a building material layer adjacent to a previously formed object cross-section, as well as smoothing the building material layer surface in preparation of forming the next object cross-section. Depending on the coating technique used, suitable materials include transformable liquids such as thermally polymerizable resins, photopolymerizable resins, a first part of a two-part epoxy, sinterable powders, bindable powders or combinations thereof and the like. Liquid materials may also contain inert filler materials.

Various forms of synergistic stimulation may be used as long as the building material is responsive to the synergistic stimulation. These include certain wavelengths of electromagnetic radiation, such as infrared radiation, visible radiation and ultraviolet radiation. Other forms of synergistic stimulation which may be used are particle beams, reactive chemicals dispensed onto the building material such as a photoinitiator (the second element of a two-part epoxy), binder materials, and the like.

The design data, representative of the three-dimensional object can be obtained from various sources including CAD data, CAT scan data, manually programmed data, and data derived from techniques for scanning physical objects. If this data is initially in layer form, the compilation process may be reduced to creating appropriate layer fill data. However, additional compilation may be desired or required to transform the data into proper form to meet accuracy, process or other requirements such as how supports will be built along with the object. The procedures and apparatus described in U.S. Pat. Nos. 5,182,055, 5,184,307, 5,192,469, 5,209,878, 5,238,639, 5,256,340, 5,273,691 and 5,321,622, 5,345,391, and U.S. patent application Ser. No. 08/233,026, pending, and Ser. No.08/233,027, pending, both filed Apr. 25, 1994, address the generation of appropriate layer data. All of these patents and patent applications are incorporated by reference as if fully set forth herein. Also incorporated by reference as if fully set forth herein, is the publication entitled Rapid Prototyping & Manufacturing: Fundamentals of Stereolithography, First Edition, authored by Paul F. Jacobs, Ph.D., and published by the Society of Manufacturing Engineers, Dearborn, Mich., in 1992.

The current invention is directed primarily to step (4) above, i.e., coating a building material layer adjacent to a previously formed object cross-section in preparation for forming a subsequent object cross-section. Several approaches have been used in the past to perform this coating step, most often with a building material comprising a liquid photopolymerizable resin. However, these prior approaches have resulted in varying degrees of layer accuracy and nonuniformity, and/or have required excessive time to form the coatings, these problems have the following ramifications:

First, it is important that the building material layer is uniform and of appropriate thickness so that upon solidification, the resulting object cross-section exhibits dimensional accuracy. Indeed, the accuracy of the successive building material layers directly impacts the accuracy of the final object in view of potential misplacement of object features upon exposure to synergistic stimulation and potential accumulated errors which may result from errors on successive layers.

Second, it is desirable to minimize the time required to form a building material layer because the cumulative coating time of the successive layers represents a significant portion of the overall object build time. Indeed, photopolymer resins exhibit slow flow velocities due to viscosity and surface tension. If driven only by gravity, imperfections in photopolymer building material layer surfaces can take prohibitively long time periods to relax or otherwise become uniform with the rest of the building material layer surface. This in turn increases object build time, reduces machine throughput, and reduces the cost effectiveness of solid imaging.

EXHIBIT B3

Special Master's Specification Support for the '537 Patent, Claim 81, Means-Plus-Function Limitation 10:

U.S. Patent No. 5,174,931 (incorporated by reference in the '537 Patent)

- **'931 Patent (cover page)**
- **'931 Patent, Figure 2**
- **'931 Patent, col. 8, ll. 17-26**

US005174931A

United States Patent [19]

Almquist et al.

[11] Patent Number: 5,174,931

[45] Date of Patent: Dec. 29, 1992

[54] METHOD OF AND APPARATUS FOR MAKING A THREE-DIMENSIONAL PRODUCT BY STEREOLITHOGRAPHY

[75] Inventors: Thomas A. Almquist, San Gabriel; Borzo Modrek, Montebello; Paul F. Jacobs, La Crescenta; Charles W. Lewis, Sherman Oaks; Mark A. Lewis, Valencia; Abraham Liran, Northridge, all of Calif.

[73] Assignee: 3D Systems, Inc., Valencia, Calif.

[21] Appl. No.: 515,479

[22] Filed: Apr. 27, 1990

Related U.S. Application Data

[63] Continuation-in-part of Ser. No. 249,399, Sep. 26, 1988, abandoned, and a continuation-in-part of Ser. No. 265,039, Oct. 31, 1988, abandoned.

[51] Int. Cl.⁵ B29C 35/08; B29C 41/02

[52] U.S. Cl. .... 264/22; 73/293; 73/305; 73/319; 73/322.5; 118/100; 118/120; 118/423; 118/429; 118/500; 118/620; 118/712; 156/64; 156/272.8; 156/273.5; 156/275.5; 156/378; 156/379.6; 156/538; 250/432 R; 250/492.1; 250/577; 264/40.1; 264/308; 340/619; 340/623; 340/624; 364/476; 365/106; 365/107; 425/135; 425/174.4; 427/8; 427/356; 427/358; 427/430.1; 427/581; 427/582

[58] Field of Search .... 264/22, 40.1, 40.2, 264/236, 308, 347; 425/135, 140, 141, 147, 162, 174, 174.4; 156/64, 272.8, 273.3, 273.5, 275.5, 307.1, 378, 379.6, 538; 427/8, 53.1, 54.1, 356, 358; 118/100, 120, 407, 413, 421, 423, 429, 620, 693, 694, 720, 500; 73/293, 305, 312, 317, 319, 320, 322.5; 250/432 R, 492.1, 577; 340/619, 623, 624, 625

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Primary Examiner—Leo B. Tentoni
Attorney, Agent, or Firm—Lyon & Lyon

[57] ABSTRACT

Apparatus and methods for stereolithographically forming a three-dimensional object includes a vessel for holding a building material and a smoothing member for forming a uniform coating over a previously formed layer of the object. The smoothing member has a plurality of blades. The smoothing member is swept over a previously formed layer of the object, in at least two directions. Different clearances between the lower surface of the smoothing member and the upper surface of the previously formed layer are used to provide a uniform coating for a subsequent layer over the previously formed layer. The sweeping velocity of the smoothing member can be varied. Retractable needles are attached to the smoothing member for adjusting a blade gap between the lower surface of the smoothing member and the surface of the building material.

54 Claims, 21 Drawing Sheets

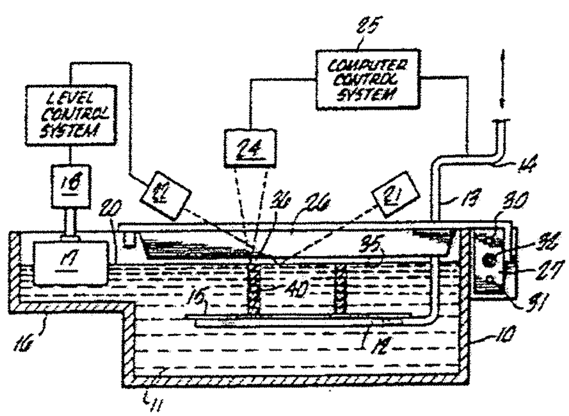

FIG. 1.

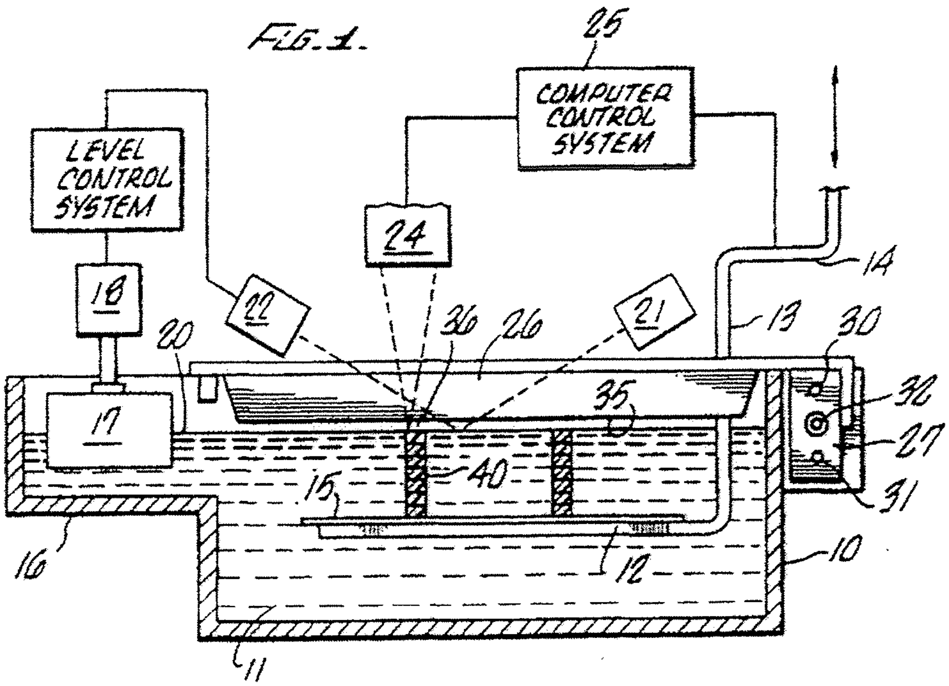
COMPUTER CONTROL SYSTEM
LEVEL CONTROL SYSTEM
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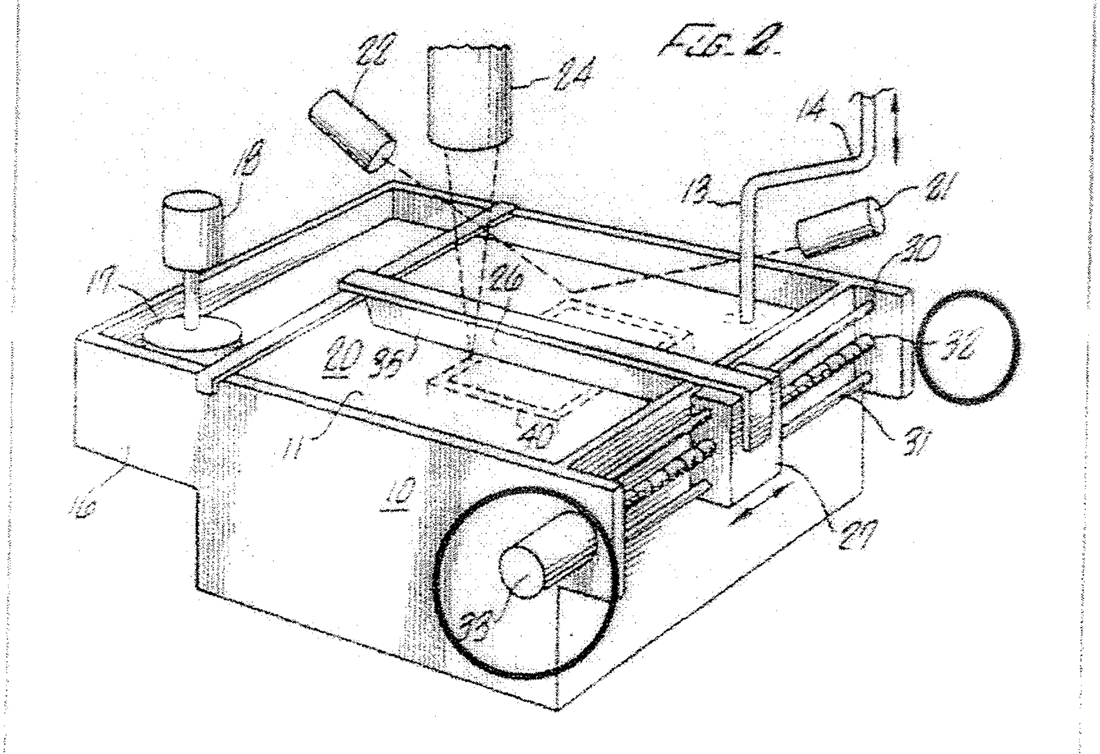
FIG. 2.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the invention under conditions of changing fluid level and angle of incidence;

FIG. 11 is a front elevational view of a bi-cell photo sensor used in a preferred embodiment of the invention;

FIG. 12 is a block diagram of the electronics associated with the bi-cell photosensor of a preferred embodiment of the invention;

FIG. 13 illustrates the trapped volume problem;

FIG. 14 illustrates threaded, retractable pins for setting the blade gap;

FIG. 15 provides a close-up view of the pin mounted in the blade;

FIG. 16 illustrates a cross-section of a blade having an angle of attack in the direction of blade movement;

FIGS. 17-19 illustrate alternative cross-sectional shapes for the blade of FIG. 16;

FIG. 20 illustrates an alternative shape for a level-detecting float;

FIG. 21 illustrates a level detecting apparatus including a float;

FIG. 22 is a diagram of the optical detector of the apparatus of FIG. 21; and

FIGS. 23(A), 23(B) and 23(C) are flowcharts of the recoating software used in one embodiment of the SLA-250;

FIGS. 24(A), 24(B), and 24(C) illustrate problems encountered with a conventional blade design having a rectangular cross-section;

FIGS. 25 illustrates how a non-vertical blade side opposite to the sweep direction will reduce the deposit of a resin hump on the leading edge of a part;

FIG. 26 illustrates a "winged" embodiment of a blade design having two contacting members;

FIGS. 27(A) and 27(B) illustrate how a preferred "Trident" embodiment of a blade design having three contacting members can reduce resin flowback and scoopout;

FIG. 28 illustrates the scoopout problem with a conventional blade design;

FIGS. 29(A), 29(B), and 29(C) illustrate embodiments of blade designs having more than three contacting members; and

FIGS. 30(A), 30(B), and 30(C) are flowcharts of the recoating software used in a second embodiment of the SLA-250.

DETAILED DESCRIPTION OF THE INVENTION

RECOATING IN GENERAL

FIGS. 1 and 2 schematically illustrate a stereolithography system for forming three-dimensional objects which embodies features of the invention of U.S. patent application Ser. No. 249,399. As shown in these drawings, tank or vat 10 is provided to contain a bath 11 of polymerizable fluid. An object support platform 12 is disposed within the tank 10 and is adapted by frame elements 13 and 14 to be raised and lowered within the tank by a motor (not shown). The platform 12 has a horizontal surface 15 on which the three-dimensional objects are formed in accordance with the invention. The tank 10 has a trough 16 in the upper portion of one sidewall of tank 10 and a plunger or piston 17 is disposed within the trough to be raised and lowered by motor 18 to control the level of the upper surface 20 of polymerizable liquid within the tank 10.

The level of the upper surface 20 of the bath 11 is detected by means of a radiation source 21 such as an HeNe laser, which is directed toward the upper surface 20 at an angle and radiation sensor 22 which may be a bi-celled detector. The position of the sensor 22 is adjusted to be at a complementary angle with respect to the upper surface 20 so as to receive the radiation from the HeNe laser. A control system 23 is provided to control the movement of the plunger 17 by motor 18.

A computer controlled radiation source 24 is disposed above the bath 11 to direct curing media, such as ultraviolet radiation or other types of curing stimulation, in a predetermined pattern across the upper surface 20 of the bath 11 in order to selectively cure the liquid building material where such radiation impacts thereon. The movement and operation of the radiation source 24 and raising and lowering of the object support platform 12 are integral parts of the computer control 25 of the system as will be further described hereinafter.

A doctor blade 26 is mounted on the top of the tank 10 and is adapted to move horizontally across the top of the tank. A blade support 27 is solidifiably mounted on rails 30 and 31 disposed along one side of the tank 10. A threaded drive shaft 32 passes through a threaded passageway (not shown) in the blade support 27 and rotation thereof by motor 33 moves the blade support 27 and thus the blade 26 horizontally across the top of the tank 10.

The operation of the stereolithography system shown in FIGS. 1 and 2 is best shown in the sequence of FIGS. 3-6. Starting with FIG. 3 the stereolithography procedure is initiated with the object support platform 12 being positioned within the bath 11 of polymerizable liquid so that the horizontal surface 15 thereon is located a short distance from the upper surface 20 of the bath. This distance is greater than the desired thickness of the layer of polymerizable liquid to be cured. The layer of polymerizable liquid immediately above the surface 15 will form the first solid layer of the three-dimensional object when cured.

This first layer above support platform 12 as well as several layers thereafter generally consist of supports that will be removed after the part has been built. Therefore, minor inaccuracies in layer thickness formed for these first few layers are inconsequential to the accurate production of the desired part.

The next step in the process is shown in FIG. 4. The object support platform 12 is raised so that the layer 34 of polymerizable liquid on the surface 15 is held above the upper surface 20 of the bath 11. The polymerizable liquid is relatively viscous fluid so the liquid does not immediately run off the edges of the surface 15 on platform 12 when the layer is raised out of the bath. Doctor blade 26 is moved horizontally so that the lower edge 35 thereof strikes off excess polymerizable liquid from the layer 34 and thereby smooths the upper surface (36) of the coating of material over surface 15. Suitable blade speeds are empirically determined to provide a desired level to the upper surface 36. Moreover, one or more passes by the doctor blade 26 may be needed at a particular speed to provide a smooth level upper surface 36 of coating 34. Typical blade speeds may range from about ½ to ten inches per second.

After the upper surface 36 of layer 34 is leveled by the doctor blade 26, the object and support platform 12 are lowered into the bath 11 as shown in FIG. 5 so that the smoothed upper surface 36 of the layer 34 is level with or in the same horizontal plane as the surface 20 of the bath 11. Together these form a surface at which additional cross-sections of a part can be formed. This

EXHIBIT C3

Special Master's Specification Support for the '143 Patent, Claim 35, Means-Plus-Function Limitation 8:

- **'143 Patent (cover page)**
- **'143 Patent, Figures 3-6**
- **'143 Patent, col. 10, ll. 13-56; col. 11, l. 46 to col. 12, l. 23; col. 12, ll. 51-61; and col. 12, l. 67 to col. 13, l. 48**

United States Patent [19]

Hull et al.

[11] Patent Number: 4,999,143

[45] Date of Patent: Mar. 12, 1991

[54] METHODS AND APPARATUS FOR PRODUCTION OF THREE-DIMENSIONAL OBJECTS BY STEREOLITHOGRAPHY

[75] Inventors: **Charles W. Hull**, Arcadia; **Charles W. Lewis**, Van Nuys, both of Calif.

[73] Assignee: **3D Systems, Inc.**, Valencia, Calif.

[21] Appl. No.: **182,801**

[22] Filed: **Apr. 18, 1988**

[51] Int. Cl.[5] **B29C 35/08**

[52] U.S. Cl. **264/22**; 264/308; 425/174.4; 427/54.1; 156/273.3

[58] Field of Search 264/22, 25, 40.1, 250, 264/255, 308, 298; 425/174.4; 427/43.1, 54.1; 365/106, 107, 119, 120, 127; 156/58, 273.3, 273.5, 275.5

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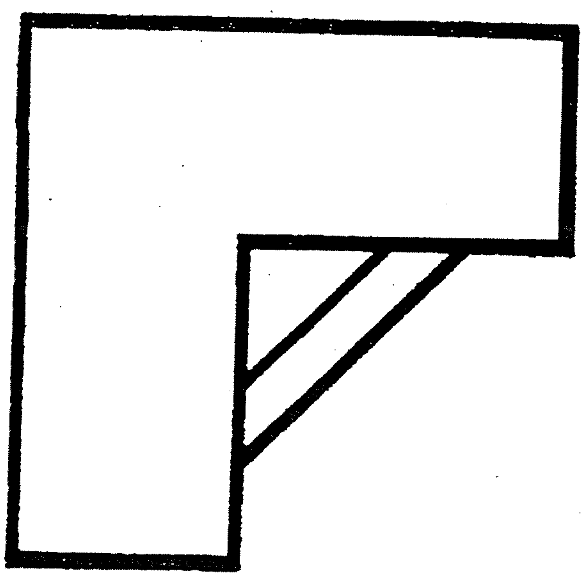
Primary Examiner—Mary Lynn Theisen
Attorney, Agent, or Firm—Lyon & Lyon

[57] ABSTRACT

An improved stereolithography system for generating a three-dimensional object by creating a cross-sectional pattern of the object to be formed at a selected surface of a fluid medium capable of altering its physical state in response to appropriate synergistic stimulation by impinging radiation, particle bombardment or chemical reaction, information defining the object being specially tailored to provide built-in supports for the object, reduce curl and distortion, and increase resolution, strength, accuracy, speed and economy of reproduction, the successive adjacent laminae, representing corresponding successive adjacent cross-sections of the object, being automatically formed and integrated together to provide a step-wise laminar buildup of the desired object, whereby a three-dimensional object is formed and drawn from a substantially planar surface of the fluid medium during the forming process.

46 Claims, 6 Drawing Sheets



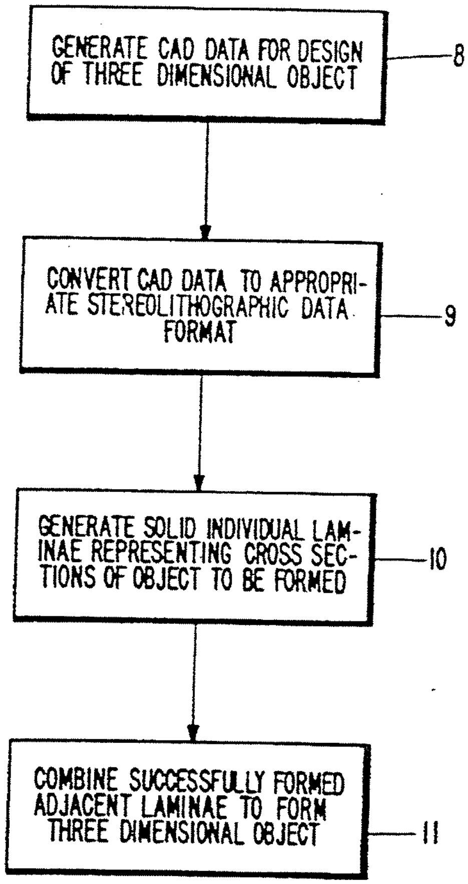

GENERATE CAD DATA FOR DESIGN OF THREE DIMENSIONAL OBJECT
8
CONVERT CAD DATA TO APPROPRIATE STEREOLITHOGRAPHIC DATA FORMAT
9
GENERATE SOLID INDIVIDUAL LAMINAE REPRESENTING CROSS SECTIONS OF OBJECT TO BE FORMED
10
COMBINE SUCCESSFULLY FORMED ADJACENT LAMINAE TO FORM THREE DIMENSIONAL OBJECT
11

FIG. 2.

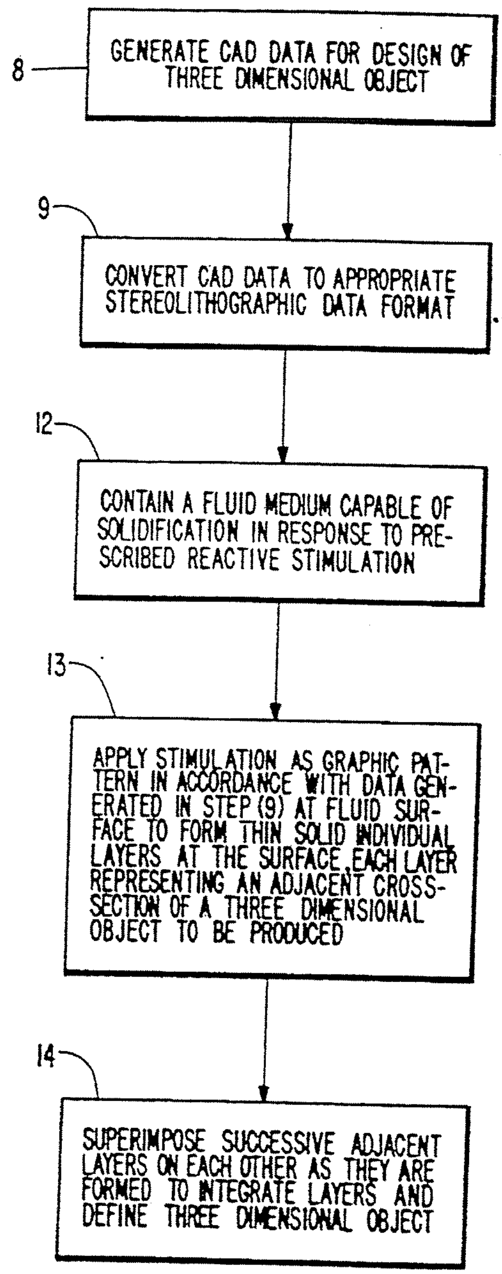
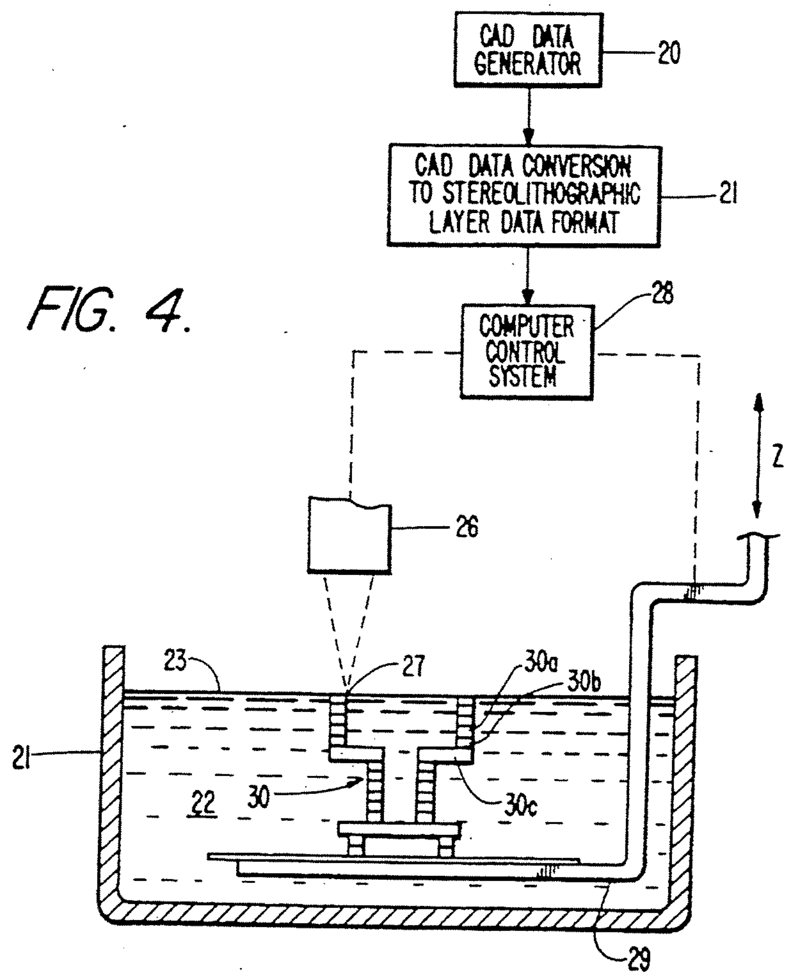

8
GENERATE CAD DATA FOR DESIGN OF THREE DIMENSIONAL OBJECT
9
CONVERT CAD DATA TO APPROPRIATE STEREOLITHOGRAPHIC DATA FORMAT
12
CONTAIN A FLUID MEDIUM CAPABLE OF SOLIDIFICATION IN RESPONSE TO PRESCRIBED REACTIVE STIMULATION
13
APPLY STIMULATION AS GRAPHIC PATTERN IN ACCORDANCE WITH DATA GENERATED IN STEP (9) AT FLUID SURFACE TO FORM THIN SOLID INDIVIDUAL LAYERS AT THE SURFACE, EACH LAYER REPRESENTING AN ADJACENT CROSS-SECTION OF A THREE DIMENSIONAL OBJECT TO BE PRODUCED
14
SUPERIMPOSE SUCCESSIVE ADJACENT LAYERS ON EACH OTHER AS THEY ARE FORMED TO INTEGRATE LAYERS AND DEFINE THREE DIMENSIONAL OBJECT

FIG. 3.

FIG. 4.



CAD DATA GENERATOR
20
CAD DATA CONVERSION TO STEREOLITHOGRAPHIC LAYER DATA FORMAT
21
28
COMPUTER CONTROL SYSTEM
Z
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30a
30b
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22
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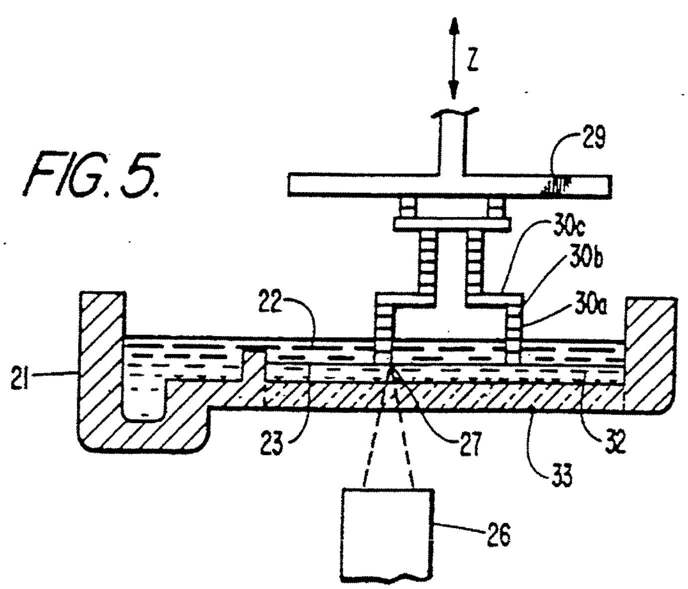
30c
29

FIG. 5.



Z
29
30c
30b
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30a
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33
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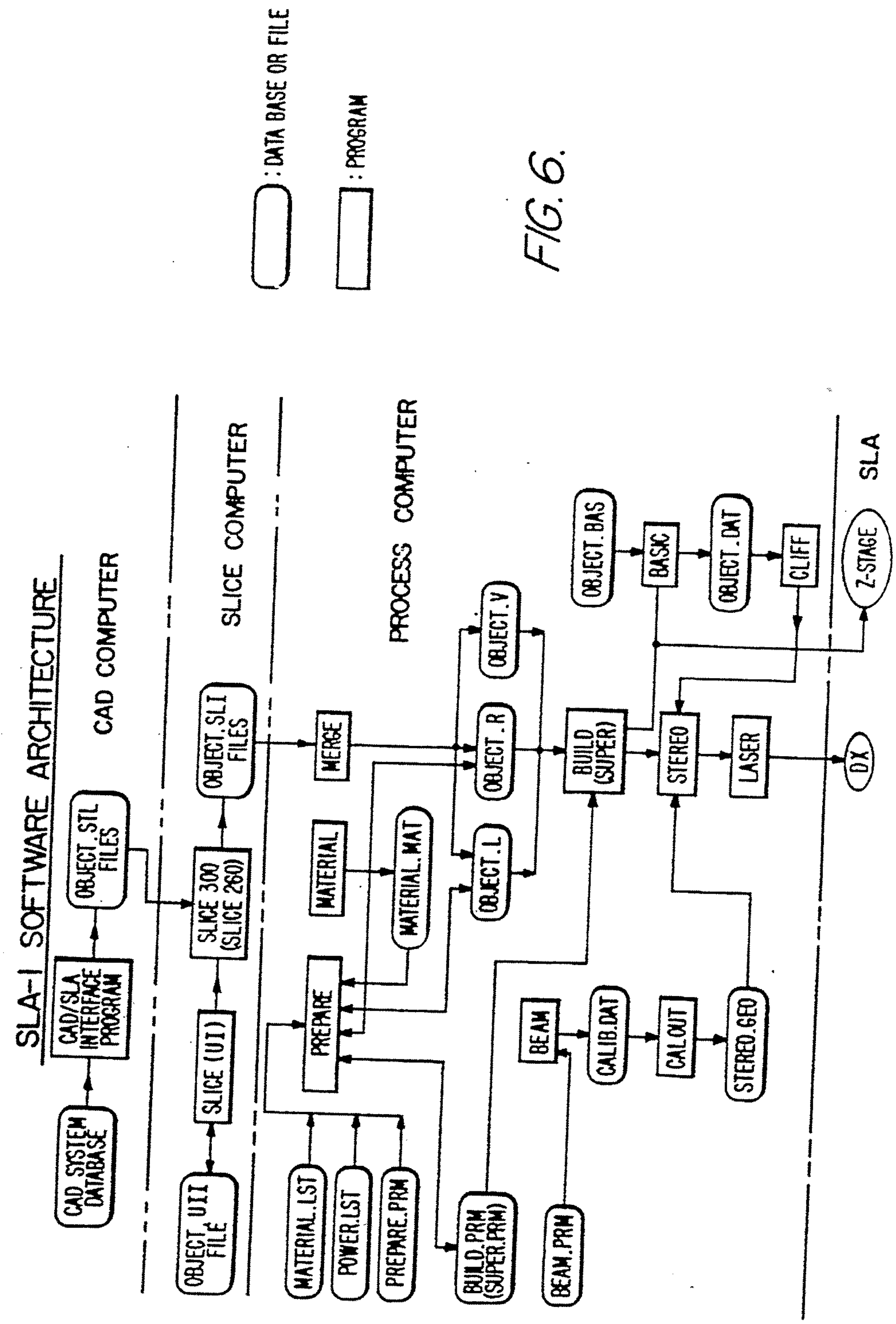
SLA-I SOFTWARE ARCHITECTURE
CAD COMPUTER
SLICE COMPUTER
PROCESS COMPUTER
SLA
: DATA BASE OR FILE
: PROGRAM
CAD SYSTEM DATABASE
CAD/SLA INTERFACE PROGRAM
OBJECT.STL FILES
OBJECT.UII FILE
SLICE (UII)
SLICE 300 (SLICE 260)
OBJECT.SLI FILES
MERGE
MATERIAL
MATERIAL.MAT
PREPARE
MATERIAL.LST
POWER.LST
PREPARE.PRM
BUILD.PRM (SUPER.PRM)
OBJECT.V
OBJECT.R
OBJECT.L
BUILD (SUPER)
OBJECT.BAS
BASIC
OBJECT.DAT
CLIFF
STEREO
LASER
BEAM
CALIB.DAT
CALOUT
STEREO.GEO
BEAM.PRM
Z-STAGE
DX

FIG. 6.

rently used as ink for high speed printing, in processes of coating of paper and other materials, such as adhesives, and in other specialty areas.

Lithography is the art of reproducing graphic objects, using various techniques. Modern examples include photographic reproduction, xerography, and microlithography, as is used in the production of microelectronics. Computer generated graphics displayed on a plotter or a cathode ray tube are also forms of lithography, where the image is a picture of a computer coded object.

Computer aided design (CAD) and computer aided manufacturing (CAM) are techniques that apply the abilities of computers to the processes of designing and manufacturing. A typical example of CAD is in the area of electronic printed circuit design, where a computer and plotter draw the design of a printed circuit board, given the design parameters as computer data input. A typical example of CAM is a numerically controlled milling machine, where a computer and a milling machine produce metal parts, given the proper programming instructions. Both CAD and CAM are important and are rapidly growing technologies.

A prime object of the present invention is to harness the principles of computer generated graphics, combined with UV curable plastic and the like, to simultaneously execute CAD and CAM, and to produce three-dimensional objects directly from computer instructions. This invention, referred to as stereolithography, can be used to sculpture models and prototypes in a design phase of product development, or as a manufacturing device, or even as an art form. The present invention enhances the developments in stereolithography set forth in U.S. Pat. No. 4,575,330, issued Mar. 11, 1986, to Charles W. Hull, one of the inventors herein.

Referring now more specifically to FIG. 2 of the drawing, the stereolithographic method is broadly outlined. Step 8 calls for generation of CAD or other data, typically in digital form, representing a three-dimensional object to be formed by the system. This CAD data usually defines surfaces in polygon format, triangles and normals perpendicular to the planes of those triangles, e.g., for slope indications, being presently preferred, and in a presently preferred embodiment of the invention conforms to the Programmer's Hierarchial Interactive Graphics System (PHIGS) now adapted as an ANSI standard. This standard is described, by way of example in the publication "Understanding PHIGS", published by Template, Megatek Corp., San Diego, Calif.

In Step 9, the PHIGS data or its equivalent is converted, in accordance with the invention, by a unique conversion system to a modified data base for driving the stereolithography output system in forming three-dimensional objects. In this regard, information defining the object is specially processed to reduce stress, curl and distortion, and increase resolution, strength and accuracy of reproduction

Step 10 in FIG. 2 calls for the generation of individual solid laminae representing cross-sections of a three-dimensional object to be formed. Step 11 combines the successively formed adjacent lamine to form the desired three-dimensional object which has been programmed into the system for selective curing.

Hence, the stereolithographic system of the present invention generates three-dimensional objects by creating a cross-sectional pattern of the object to be formed at a selected surface of a fluid medium, e.g., a UV curable liquid or the like, capable of altering its physical state in response to appropriate synergistic stimulation such as impinging radiation, electron beam or other particle bombardment, or applied chemicals (as by ink jet or spraying over a mask adjacent the fluid surface), successive adjacent laminae, representing corresponding successive adjacent cross-sections of the object, being automatically formed and integrated together to provide a step-wise laminar or thin layer buildup of the object, whereby a three-dimensional object is formed and drawn from a substantially planar or sheet-like surface of the fluid medium during the forming process.

The aforedescribed technique illustrated in FIG. 2 is more specifically outlined in the flowchart of FIG. 3, where again Step 8 calls for generation of CAD or other data, typically in digital form, representing a three-dimensional object to be formed by the system. Again, in Step 9, the PHIGS data is converted by a unique conversion system to a modified data base for driving the stereolithography output system in forming three-dimensional objects. Step 12 calls for containing a fluid medium capable of solidification in response to prescribed reactive stimulation. Step 13 calls for application of that stimulation as a graphic pattern, in response to data output from the computer 4 in FIG. 1, at a designated fluid surface to form thin, solid, individual layers at that surface, each layer representing an adjacent cross-section of a three-dimensional object to be produced. In the practical application of the invention, each lamina will be a tin lamina, but thick enough to be adequately cohesive in forming the cross-section and adhering to the adjacent laminae defining other cross-sections of the object being formed.

Step 14 in FIG. 3 calls for superimposing successive adjacent layers or laminae on each other as they are formed, to integrate the various layers and define the desired three-dimensional object. In the normal practice of the invention, as the fluid medium cures and solid material forms to define one lamina, that lamina is moved away from the working surface of the fluid medium and the next lamina is formed in the new liquid which replaces the previously formed lamina, so that each successive lamina is superimposed and integral with (by virtue of the natural adhesive properties of the cured fluid medium) all of the other cross-sectional laminae. Of course, as previously indicated, the present invention also deals with the problems posed in transitioning between vertical and horizontal.

The process of producing such cross-sectional laminae is repeated over and over again until the entire three-dimensional object has been formed. The object is then removed and the system is ready to produce another object which may be identical to the previous object or may be an entirely new object formed by changing the program controlling the stereolithographic system.

FIGS. 4–5 of the drawings illustrate various apparatus suitable for implementing the stereolithographic methods illustrated and described by the systems and flow charts of FIGS. 1–3.

As previously indicated, "Stereolithography" is a method and apparatus for making solid objects by successively "printing" thin layers of a curable material, e.g., a UV curable material, one on top of the other. A programmable movable spot beam of UV light shining on a surface or layer of UV curable liquid is used to form a solid cross-section of the object at the surface of the liquid. The object is then moved, in a programmed

manner, away from the liquid surface by the thickness of one layer and the next cross-section is then formed and adhered to the immediately preceding layer defining the object. This process is continued until the entire object is formed.

Essentially all types of object forms can be created with the technique of the present invention. Complex forms are more easily created by using the functions of a computer to help generate the programmed commands and to then send the program signals to the stereolithographic object forming subsystem.

The data base of a CAD system can take several forms. One form, as previously indicated, consists of representing the surface of an object as a mesh of triangles (PHIGS). These triangles completely form the inner and outer surfaces of the object. This CAD representation also includes a unit length normal vector for each triangle. The normal points away from the solid which the triangle is bounding. This invention provides a means of processing such CAD data into the layer-by-layer vector data that is necessary for forming objects through stereolithography.

For stereolithography to successfully work, there must be good adhesion from one layer to the next. Hence, plastic from one layer must overlay plastic that was formed when the previous layer was built. In building models that are made of vertical segments, plastic that is formed on one layer will fall exactly on previously formed plastic from the preceding layer, and thereby provide good adhesion. As one starts to make a transition from vertical to horizontal features, using finite jumps in layer thickness, a point will eventually be reached where the plastic formed on one layer does not make contact with the plastic formed on the previous layer, this causes severe adhesion problems. Horizontal surfaces themselves do not present adhesion problems because by being horizontal the whole section is built on one layer with side-to-side adhesion maintaining structural integrity. Therefore, means are provided for insuring adhesion between layers when making transitions from vertical to horizontal or horizontal to vertical sections, as well as providing a way to completely bound a surface, and ways to reduce or eliminate stress and strain in formed parts.

A presently preferred embodiment of a new and improved stereolithographic system is shown in elevational cross-section in FIG. 4. A container 21 is filled with a UV curable liquid 22 or the like, to provide a designated working surface 23. A programmable source of ultraviolet light 26 or the like produces a spot of ultraviolet light 27 in the plane of surface 23. The spot 27 is movable across the surface 23 by the motion of mirrors or other optical or mechanical elements (not shown in FIG. 4) used with the light source 26. The position of the spot 27 on surface 23 is controlled by a computer control system 28. As previously indicated, the system 28 may be under control of CAD data produced by a generator 20 in a CAD design system or the like and directed in PHIGS format or its equivalent to a computerized conversion system 25 where information defining the object is specially processed to reduce stress, curl and distortion, and increase resolution, strength and accuracy of reproduction.

A movable elevator platform 29 inside container 21 can be moved up and down selectively, the position of the platform being controlled by the system 28. As the device operates, it produces a three-dimensional object 30 by step-wise buildup of integrated laminae such as 30a, 30b, 30c.

The surface of the UV curable liquid 22 is maintained at a constant level in the container 21, and the spot of UV light 27, or other suitable form of reactive stimulation, of sufficient intensity to cure the liquid and convert it to a solid material is moved across the working surface 23 in a programmed manner. As the liquid 22 cures and solid material forms, the elevator platform 29 that was initially just below surface 23 is moved down from the surface in a programmed manner by any suitable actuator. In this way, the solid material that was initially formed is taken below surface 23 and new liquid 22 flows across the surface 23. A portion of this new liquid is, in turn, converted to solid material by the programmed UV light spot 27, and the new material adhesively connects to the material below it. This process is continued until the entire three-dimensional object 30 is formed. The object 30 is then removed from the container 21, and the apparatus is ready to produce another object. Another object can then be produced, or some new object can be made by changing the program in the computer 28.

The curable liquid 22, e.g., UV curable liquid, must have several important properties. (A) It must cure fast enough with the available UV light source to allow practical object formation times. (B) It must be adhesive, so that successive layers will adhere to each other. (C) Its viscosity must be low enough so that fresh liquid material will quickly flow across the surface when the elevator moves the object. (D) It should absorb UV so that the film formed will be reasonably thin. (E) It must be reasonably soluble in some solvent in the liquid state, and reasonably insoluble in that same solvent in the solid state, so that the object can be washed free of the UV cure liquid and partially cured liquid after the object has been formed. (F) It should be as non-toxic and non-irritating as possible.

The cured material must also have desirable properties once it is in the solid state. These properties depend on the application involved, as in the conventional use of other plastic materials. Such parameters as color, texture, strength, electrical properties, flammability, and flexibility are among the properties to be considered. In addition, the cost of the material will be important in many cases.

The UV curable material used in the presently preferred embodiment of a working stereolithograph (e.g., FIG. 3) is DeSoto SLR 800 stereolithography resin, made by DeSoto, Inc. of Des Plains, Ill.

The light source 26 produces the spot 27 of UV light small enough to allow the desired object detail to be formed, and intense enough to cure the UV curable liquid being used quickly enough to be practical. The source 26 is arranged so it can be programmed to be turned off and on, and to move, such that the focused spot 27 moves across the surface 23 of the liquid 22. Thus, as the spot 27 moves, it cures the liquid 22 into a solid, and "draws" a solid pattern on the surface in much the same way a chart recorder or plotter uses a pen to draw a pattern on paper.

The light source 26 for the presently preferred embodiment of a stereolithography is typically a helium-cadmium ultraviolet laser such as the Model 424 N HeCd Multimode Laser, made by Liconix of Sunnyvale, Calif.

In the system of FIG. 4, means may be provided to keep the surface 23 at a constant level and to replenish

this material after an object has been removed, so that the focus spot 27 will remain sharply in focus on a fixed focus plane, thus insuring maximum resolution in forming a layer along the working surface. In this regard, it is desired to shape the focal point to provide a region of high intensity right at the working surface 23, rapidly diverging to low intensity and thereby limiting the depth of the curing process to provide the thinnest appropriate cross-sectional laminae for the object being formed.

The elevator platform 29 is used to support and hold the object 30 being formed, and to move it up and down as required. Typically, after a layer is formed, the object 30 is moved beyond the level of the next layer to allow the liquid 22 to flow into the momentary void at surface 23 left where the solid was formed, and then it is moved back to the correct level for the next layer. The requirements for the elevator platform 29 are that it can be moved in a programmed fashion at appropriate speeds, with adequate precision, and that it is powerful enough to handle the weight of the object 30 being formed. In addition, a manual fine adjustment of the elevator platform position is useful during the set-up phase and when the object is being removed.

The elevator platform 29 can be mechanical, pneumatic, hydraulic, or electrical and may also use optical or electronic feedback to precisely control its position. The elevator platform 29 is typically fabricated of either glass or aluminum, but any material to which the cured plastic material will adhere is suitable.

A computer controlled pump (not shown) may be used to maintain a constant level of the liquid 22 at the working surface 23. Appropriate level detection system and feedback networks, well known in the art, can be used to drive a fluid pump or a liquid displacement device, such as a solid rod (not shown) which is moved out of the fluid medium as the elevator platform is moved further into the fluid medium, to offset changes in fluid volume and maintain constant fluid level at the surface 23. Alternatively, the source 26 can be moved relative to the sensed level 23 and automatically maintain sharp focus at the working surface 23. All of these alternatives can be readily achieved by appropriate data operating in conjunction with the computer control system 28.

FIG. 6 of the drawings illustrates the overall software architecture of a stereolithography system in which the present invention may be practiced.

As an overview, the portion of our processing referred to as "SLICE" takes in the object that you want to build, together with any scaffolding or supports that are necessary to make it more buildable. These supports are typically generated by the user's CAD. The first thing SLICE does is to find the outlines of the object and its supports.

SLICE defines each microsection or layer one at a time under certain specified controlling styles. SLICE produces a boundary to the solid portion of the object. If, for instance, the object is hollow, there will be an outside surface and an inside one. This outline then is the primary information. The SLICE program then takes that outline or series of outlines and says, but if you build an outside skin and an inside skin they won't join to one another, you'll have liquid between them. It will collapse. So let us turn this into a real product, a real part by putting in cross-hatching between the surfaces or solidifying everything inbetween or adding skins where there is so gentle a slope that one layer wouldn't join on top of the next, remembering past history or slope of the triangles (PHIGS) whichever way you look at it. SLICE does all those things and may use some lookup tables of the chemical characteristics of the photopolymer, how powerful the laser is, and related parameter to indicate how long to expose each of the output vectors used to operate the system. That output consists of identifiable groups. One group consists of the boundaries or outlines. Another group consists of cross-hatches. There are various subgroups of these types further described in Ser. No. 182,830. A third group consists of skins and there are subgroups of those, upward facing skins, and downward facing skins which have to be treated slightly differently. These subgroups are all tracked differently because they may get slightly different treatment, in the process the output data is then appropriately managed to form the desired object and supports.

After the three-dimensional object 30 has been formed, the elevator platform 29 is raised and the object is removed from the platform for post processing.

In addition, there may be several containers 21 used in the practice of the invention, each container having a different type of curable material that can be automatically selected by the stereolithographic system. In this regard, the various materials might provide plastics of different colors, or have both insulating and conducting material available for the various layers of electronic products.

As will be apparent from FIG. 5 of the drawings, there is shown an alternate configuration of a stereolithograph wherein the UV curable liquid 22 or the like floats on a heavier UV transparent liquid 32 which is non-miscible and non-wetting with the curable liquid 22. By way of example, ethylene glycol or heavy water are suitable for the intermediate liquid layer 32. In the system of FIG. 4, the three-dimensional object 30 is pulled up from the liquid 22, rather than down and further into the liquid medium, as shown in the system of FIG. 3.

The UV light source 26 in FIG. 5 focuses the spot 27 at the interface between the liquid 22 and the non-miscible intermediate liquid layer 32, the UV radiation passing through a suitable UV transparent window 33, of quartz or the like, supported at the bottom of the container 21. The curable liquid 22 is provided in a very thin layer over the non-miscible layer 32 and thereby has the advantage of limiting layer thickness directly rather than relying solely upon absorption and the like to limit the depth of curing since ideally an ultrathin lamina is to be provided. Hence, the region of formation will be more sharply defined and some surfaces will be formed smoother with the system of FIG. 5 than with that of FIG. 4. In addition a smaller volume of UV curable liquid 22 is required, and the substitution of one curable material for another is easier.

A commercial stereolithography system will have additional components and subsystems besides those previously shown in connection with the schematically depicted systems of FIGS. 1-5. For example, the commercial system would also have a frame and housing, and a control panel. It should have means to shield the operator from excess UV and visible light, and it may also have means to allow viewing of the object 30 while it is being formed. Commercial units will provide safety means for controlling ozone and noxious fumes, as well as conventional high voltage safety protection and interlocks . Such commercial units will also have means

CERTIFICATE OF SERVICE

I hereby certify that on August 20, 2007, I electronically filed the foregoing with the Clerk of the Court using the ECF system which will send notification of such filing to the following:

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I declare under penalty of perjury that the foregoing statements are true and correct.

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